INTERACTION BETWEEN THE CONVECTIVE SUBLAYER AND THE COLD FRACTURED SURFACE OF EUROPA'S ICE SHELL. G. Tobie[1,2], G. Choblet[2], J. Lunine[1] and C. Sotin[2] [1]Lunar and Planeary Laboratory, (1629 University Bvld, Tucson, AZ; e-mail: gtobie@lpl.arizona.edu),[2] Laboratoire de Planetologie et Geodynamique (2, rue de la houssiniere, 44322 NANTES cedex, France).

Introduction: As it travels around Jupiter on a synchronous orbit, Europa is subjected to periodic deformation due to its high orbital eccentricity (e=1%). The tidal response of its ice shell is almost uniquely controlled by the radial displacement of the underlying ocean [1]. At the base of the ice shell, ice, close to its melting point behaves like a viscoelastic medium, whereas the elastic/brittle response progressively dominates when the cold surface is approached.

Tidal stress field and brittle failure: The periodic radial displacement of the ocean induces a large tidal flexing of the ice shell. The resulting stress field would be responsible for the highly fractured appearance of Europa's surface. Usually, tidal stress is computed assuming the superficial ice shell is elastic. From the elastic response, one can show that the brittle strength of ice is exceeded at the surface of Europa [e.g., 2, 3, 4]. The downward propagation of cracks initiated at the surface is more problematic. Experimentally, the brittle and ductile domains of a material are defined from change in stress-strain curve behaviors. The transition between the two domains occurs at the train rate $\dot{e}_t$ where the brittle stress σ_b is equal to the ductile strength σ_d. Several factors can modify this transition, notably temperature, grain size, confined pressure [5].

On Europa, tidal forcing imposed in the ice shell strain rates of 10^{-10}-$2.10^{-10}.s^{-1}$, depending mainly on longitude, [6, 7]. Near the surface where the temperature is far from the melting point value, the brittle strength σ_b is weaker than the viscous strength σ_d at these strain rates, whereas $\sigma_b > \sigma_d$ toward the base of the layer. As mentionned above, the exact transition depth between the brittle layer and the ductile one depends on several parameters and on the type of crack mechanism. The lateral variations of the strain rate and of the temperature at the surface ($\dot{e}_t = 2.10^{-10}.s^{-1}$ and T_{surf}= 50K at the poles, $\dot{e}_t = 10^{-10}.s^{-1}$ and T_{surf}= 110K at the equator) modify the depth transition to some extent.

Crack nucleation and propagation are firstly limited by confined pressure, which avoids fault propagation to depth more than 1km for the elastic tidal stress value (~0.1MPa). However, the existence of cracks in the upper icy crust would modify significantly the stress field compared to the elastic case, amplifying locally the magnitude of stress. This would help the crack nucleation and propagation deeper in the ice shell.

Furthermore, the periodic forcing creates progressive fatigue of the icy material, which modifies its brittle strength [5, 6]. Simultaneously, tidal friction along activated fault creates a heat source elevating locally the temperature of the ice and making it more ductile.

Thermal convection and ductile creep: The low viscosity of ice near its melting point (~10^{13}-10^{14} Pa.s) creates large dissipation in the bottom part of the layer and can initiate convective instabilities for ice thickness as thin as 10 km. Once thermal convection occurs, almost half of the bottom part of the layer becomes dissipative. The high power dissipated by body tide in the ice shell is thus able to prevent the freezing of the ocean even if the layer is convecting. For its current eccentricity, tidal dissipation in the silicate mantle is probably negligible, and the ice layer is stabilized to a thickness of about 20-30 km [8,9]. The ice shell thus consists of an isothermal convective sublayer overlaid by a thick rigid conductive lid of around 5-10 km.

Tidal heating in the ice shell is so high that it raises the temperature in hot plumes up to the melting point temperature. This creates episodic upwelling of partially molten ice up to the base of the conductive lid [8]. The ascent of warm ice would add supplementary stress and then help the formation of fractured zone. Reciprocally, the existence of fractured zone would help the rise of partially molten ice near the surface.

Toward a self-consitent model - preliminary results: Modeling the dynamics of Europa's ice shell from the ocean to the surface required the inclusion of tidal heating due to viscous dissipation, fault formation, strain localization and heating resulting from friction along faults, and partial melting in a self-consistent way. The model developement is based on the 2D thermal convection model described in [9]. At a first attempt, we model the fractured zone in the conductive lid using simple damage parameterization. We suppose that the local viscosity of ice depends on temperature T, on partial melting x_m, and on a parameter d characterizing the degree of ice damage:

$$\eta(x,z)=\eta_0 \exp(-\gamma_T T) \exp(-\gamma_m x_m) \exp(-\gamma_d d), \quad (1)$$

η_o being the viscosity of pure ice near its melting. Tidal heating is computing directly from the effective viscosity field [8]:

$$H_{tide}(x,z)=2\,H_{max}/(\eta_{max}/\eta + \eta / \eta_{max}), \qquad (2)$$

where H_{max} *is the maximum dissipation value that occurs for viscosity equal to* $\eta_{max} = \mu/\omega = 1.5\mathrm{x}10^{14}$ Pa.s on Europa (μ =3.3x10^9 Pa, w=2.10^{-5} rad.s^{-1}).

For the example presented on Figure 1, we suppose a constant distribution of damage d localized in the conductive lid, at x=20km. This simulates a zone of weakness in the rigid lid extending from the surface down to a depth of 5 km. At the middle of this zone (x=20 km), the parameter d is equal to 1 and it decreases exponentially on both sides. In this weakness zone, the effective viscosity is reduced by a factor of 10. The fall of the effective viscosity increases locally the amount of tidal heating and favors the rise of warm ice up to shallow depths (< 2 km) (Figure 1). The rise of this hot plume increases locally the heat flux up to about 100-150 mW.m^{-2}. It also generates locally an upward stress of around 0.1 MPa, inducing a bump of around 50m magnitude.

This preliminary result indicates the importance of tidal strain localization in the conductive lid on convective instabilities, and the strong mechanical and thermal coupling that exists between tidal deformation and thermal convection. We are currently incorporating these different aspects in our numerical model in order to better understand the link between the convective instabilites in the icy layer and the highly fractured surface of Europa.

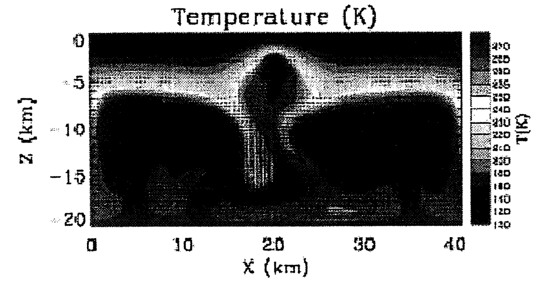

Figure 1: Temperature field obtained with our 2D thermal convection model including a weakness zone in the conductive lid and viscosity dependent tidal heating. (model parameter: Ra=6.10^6, $\Delta\ \eta$ =1.2x10^6, h0=3.75x10^{13} Pa.s, b=20 km)

References:

[1] Tobie G., Mocquet A. and Sotin C. (2003a) Icarus, submitted. [2] Helfenstein and Parmentier (1983) Icarus, 53, 415-430. [3] Greenberg et al. (1998) Icarus, 135, 64-78. [4] Schulson (2002), J. Geophys. Res., 107, 17-1. [5] Schulson (2001), Eng. Frac. Mech., 68, 1839-1887. [6] Weber and Nixon (1997) Cold Reg. Sci. Tech., 26, 153-164. [7] Ojakangas and Stevenson (1989), Icarus, 81, 220-241. [8] Tobie G., Choblet G. and C. Sotin (2003), J. Geophys. Res., in press. [9] Hussmann H. et al. (2002) Icarus, 156, 143-151.